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THE DEVELOPMENT AND SCIENTIFIC IMPACT OF THE *CHANDRA* X-RAY OBSERVATORY

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I review the operational capabilities of the *Chandra* X-ray Observatory, including some of the spectacular results obtained by the general observer community. A natural theme of this talk is that *Chandra* is revealing outflows of great quantities of energy that were not previously observable. I highlight the *Chandra* studies of powerful X-ray jets. This subject is only possible due to the sub-arcsecond resolution of the X-ray telescope.

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1. Development of the *Chandra* X-ray Observatory

The Advanced X-ray Astrophysics Facility (*AXAF*) was developed to serve the entire astronomical community for attacking a wide range of problems.^{1,2,3} The requirements to do this included large telescope area, access to the entire sky with more than 85% available at any time, high observing efficiency and a long operational lifetime, instruments which could provide imaging and spectroscopy, including spatially resolved spectroscopy with at least modest ($E/\Delta E \approx 10$ to 50) energy resolution, and the ability to locate the measured photons on the sky. However, by far the most stringent and crucial requirement was for the telescope to be able to image to better than $0.5''$ FWHM. More precisely, it was required that a $1''$ diameter circle about a point source would contain 70%, and 20%, of the photons imaged at 1 and at 8 keV, respectively. This allows high contrast for large dynamic range, and gives an imaging point spread function (PSF) which is not a strong function of energy. Prior to launch, *AXAF* was renamed the *Chandra* X-ray Observatory (CXO), in honor of the Indian-American astrophysicist Subramanyan Chandrasekhar.

The exquisite X-ray imaging capability of the High Resolution Mirror Assembly (HRMA) is the key to the scientific power of the *Chandra* observatory. Imaging to $0.5''$ in contrast to the $\sim 5''$ imaging capability of the previous *Einstein* and *ROSAT* X-ray missions, is truly a 100-fold improvement in the imaging capability. This enables *Chandra* to study jets and outflows in quasars and active galaxies which had previously been considered “point” sources, to reveal structure and interactions

within clusters of galaxies for which the distribution of hot gas had previously been considered smooth and symmetric, and to allow point source detection to fluxes 100 times fainter due to the reduction of the detector area which accumulates background.

One of two different imaging instruments can be moved into the telescope aim point at any time. The High Resolution Camera (HRC) uses micro channel plates (MCP) to convert the X-ray, and to amplify the resulting electrons. The X-ray is located by determining the centroid of the resulting electron cloud. The Advanced Camera for Imaging Spectroscopy (ACIS, formerly the “AXAF Camera for Imaging Spectroscopy”), uses charge coupled devices (CCD) to convert X-rays into a number of electrons directly proportional to the photon energy, and clocks these out in a fixed pattern which indicates the position at which the X-ray was imaged. A low energy transmission grating (LETG) gives dispersive resolution optimized for the 0.07 to 2 keV range, while a high energy transmission grating (HETG) consists of two separate sets of gratings optimized for the 0.4 to 5 keV range (medium energy grating) and the 0.8 to 10 keV range (high energy grating). If desired, either the LETG or HETG (but not both!) can be inserted into the optical path.

A unique feature of celestial X-ray astronomy is that it is based on single photon counting. The energies are large enough, from 0.1 to 10 keV in the case of *Chandra*, that this is possible, and from most celestial sources the fluxes are so low that it is imperative. At the limiting sensitivity in the deepest fields, 10 photons in a two week integration represents a significant detection. Operationally this means that the satellite need not point rigidly to within a very small fraction of the desired resolution for the duration of the exposure. In fact, it is desirable to force the telescope to dither over many pixels in order to use an averaged calibration, since it is not feasible to calibrate each resolution element to the accuracy ultimately desired. An optical CCD camera which simultaneously measures stars on the sky and fiducial lights on the instruments enables post facto ground reconstruction of the image to better than $0.1''$.

2. *Chandra* Studies of Energy Outflows

X-ray astronomy, and *Chandra* in particular, studies virtually every type of astronomical system. To limit the scope of this review I have chosen some examples where the *Chandra* observations are giving us information on the outflow of matter and energy. This presents a contrast to much of the historical impact of X-ray astronomy, which has been to elucidate accretion processes on compact, binary stars in our galaxy, and on supermassive black holes in active galactic nuclei (AGN). Specifically, I will show some results on supernovae and pulsar wind nebulae, on X-ray “cavities” found in clusters of galaxies and the fate of cooling flows of gas in those clusters, and on X-ray jets seen in quasars and powerful FR II radio galaxies and the implication that these may serve as “cosmological beacons.”

2.1. Pulsar wind nebulae

Gaensler⁵ has recently reviewed the winds expelled from pulsars, bringing to bear multifrequency radio, optical, and X-ray observations. From the early radio observation of pulsars, and their interpretation as neutron stars, the rate of period increases led to a realization that up to 10^{39} ergs s⁻¹ of rotational energy was being lost. This dwarfed the amount of energy detected as electromagnetic emission across the radio to γ -ray spectrum. Theory suggested that the bulk of the power went into acceleration of relativistic particles⁶ and generation of a wind.⁷ The wind would emanate from the speed of light circle at radius $r = c/f$, where c is the speed of light and f the pulsar frequency. This region cannot be imaged, being much smaller than microarcseconds.

What has now been observed, as shown in Figure 1 for the Crab Nebula, is the termination shock where the relativistic wind hits the nebula ejected by the supernova. The apparently concentric rings indicate an outflow, which can be assumed as equatorial by symmetry. The jet which appears perpendicular to the rings must be associated with the rotational axis, as the magnetic axis must sweep a wide region on the sky in order to modulate the pulses.

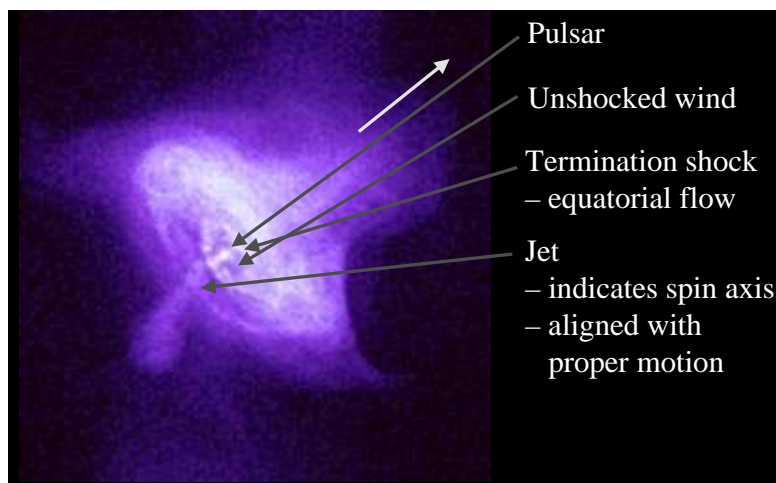


Fig. 1. *Chandra* image of the Crab Nebula (NASA/CXC/MSFC from Ref. 4), showing the pulsar, the termination shock from the relativistic equatorial wind, and the jet. The large arrow shows the direction of the spin axis and the proper motion.

The structure of the Crab Nebula wind and jet is known to have remarkable optical and X-ray variations, and apparent motions at half the speed of light.⁸ The Vela Pulsar Nebular also shows a remarkable time sequence of changes in its outer jet (Figure 2).⁹ From this one can infer apparent relativistic motion⁹ of $0.35c$ and $0.51c$ for the blobs A and B, respectively, in Figure 2.

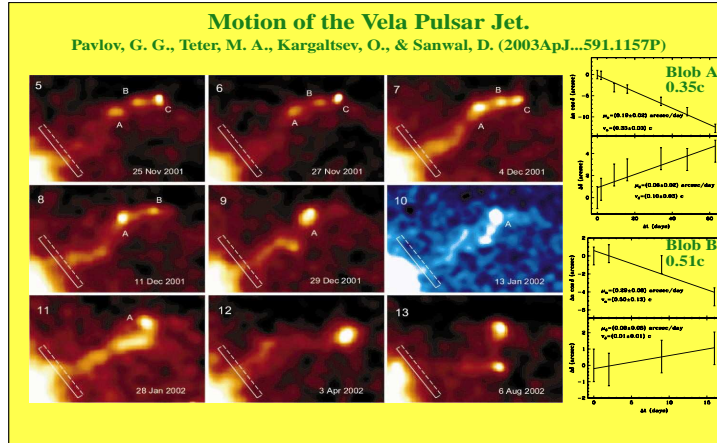


Fig. 2. Sequence of *Chandra* images of the outer jet of the Vela pulsar (from Ref. 9) showing changes in morphology, and systematic outward motions.

2.2. Cooling flows in clusters of galaxies

A major problem on which *Chandra* has provided key data is that of cooling flows in clusters of galaxies (e.g., Ref. 10). Hot gas of temperature $\sim 10^8$ K fills rich clusters of galaxies, and emits X-rays via thermal bremsstrahlung. From the X-ray surface brightness, one can deduce the electron density profile. Typically, in the core of the cluster the density is sufficiently high that the cooling time becomes much less than the Hubble time. This implies that the cooled gas should fall into the cluster core, becoming more dense and cooling at an ever increasing rate. Indeed, the X-ray brightness profile of such clusters shows emission highly peaked at the cluster center. Infall rates in excess of 100 solar masses per year were often deduced.¹¹ However, the destination of the gas was a mystery. Star formation rates were no more than 10 solar masses per year. Spectroscopic observations did not reveal the line emission expected from X-ray emitting gas at temperatures below 1 to 2 keV.

It now seems that “cavities,” depressions seen in the X-ray surface brightness, are indicators of energy input from the central radio source. These cavities, also called “holes” or “bubbles,” were first detected in *ROSAT* observations of the Perseus Cluster,¹² and are detected by *Chandra* in at least 18 cluster atmospheres.¹³

Figure 3, from Refs. 14 and 15, shows studies of the Hydra A cluster. The association of cooling flows with central powerful radio sources had been documented,¹⁶ and it had been suggested that the energy from radio sources in a central cD galaxy could balance the radiative losses and stop the cooling flows, (e.g., Ref. 17). In this picture, it was assumed that a radio jet would cause shock heating upon colliding with the cluster gas.^{18,19} Consistent with this prediction, the lower left panel in Figure 3 shows a two-sided, 5 GHz jet²⁰ from the central galaxy entering the two main cavities and filling them with radio plasma. However, contrary to the predictions, the higher density gas around the cavity rims is at a *lower* temperature than the

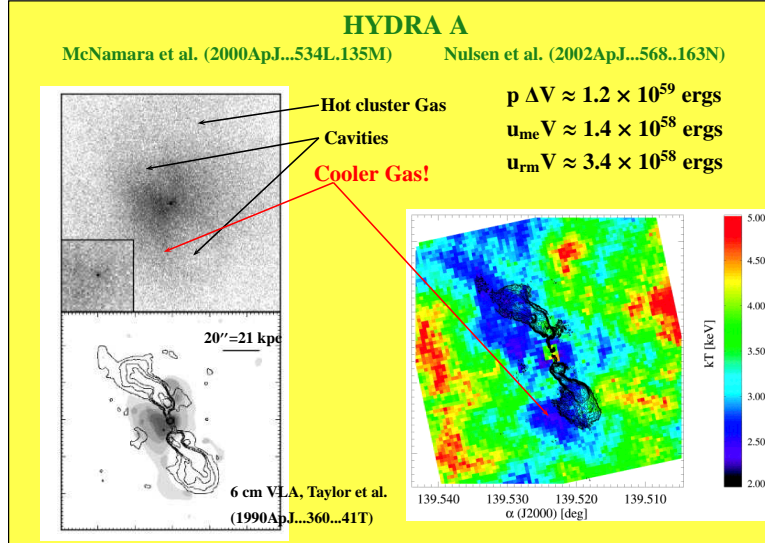


Fig. 3. X-ray and radio images of the center of the Hydra A cluster of galaxies.

ambient cluster gas, as shown in the lower right hand panel¹⁵ in Figure 3.

The interpretation is that these cavities are bubbles inflated by work done by the radio jet, and which are now rising buoyantly through the cluster. Since the volume is directly observed, assuming rotational symmetry, and the gas density and temperature are deduced from the X-ray surface brightness and spectrum, one can calculate the work done to expand the cavity. For the northern Hydra A cavity, $p\Delta V = kT\Delta V \approx 1.2 \times 10^{59}$ ergs. However, if one deduces the minimum energy density in particles and magnetic field which gives the observed radio emission, only about 1.4×10^{58} ergs is available. In the case of the Perseus Cluster, the discrepancy is almost two orders of magnitude between the work $p\Delta V \approx 2 \times 10^{58}$ to evacuate the North cavity and the available minimum energy. These are not necessarily discrepancies. The radio plasma may deviate from the many assumptions made to carry out the equipartition calculation. In the case of Hydra A, Ref. 20 argue that the rotation measure implies a magnetic field several times less than equipartition, giving a total energy several times larger. Also, the above calculations all ignored the bulk kinetic flux which might have been carried by a relativistic jet. In the next section, we will see that bulk relativistic motion in the jet is probably a general feature of quasars and FR II radio sources, and may carry a kinetic energy flux exceeding the radiative luminosity.

2.3. X-ray jets in quasars

Prior to *Chandra*, extragalactic X-ray jets had been detected in the famous objects Cen A, M87, and 3C 273. The sub-arcsecond imaging capability of *Chandra* has

opened up the general study of X-ray jets in radio sources. Although jets may extend $5''$ to $20''$ from the quasar or radio galaxy, their surface brightness is lost in the core PSF when the latter is larger than a few arcseconds, because the jet flux is typically only one to a few percent that of the core. In general, for the low power, FR I type radio sources the X-ray jet emission can be interpreted as an extension of the radio synchrotron emission.²¹ Here I will discuss only the powerful, FR II galaxies and quasars.

Chandra has made many serendipitous observations of jets, e.g. in PKS 0637-752,²² PKS 1127-143,²³ and GB 1508+5714,²⁴ and has pointed at some of the well known objects, notably 3C 273.²⁵ Two groups^{26,27} have attempted systematic X-ray studies of FR II type radio jets. I will discuss four objects from the latter survey to illustrate the conditions which are generally being derived for these systems.²⁸

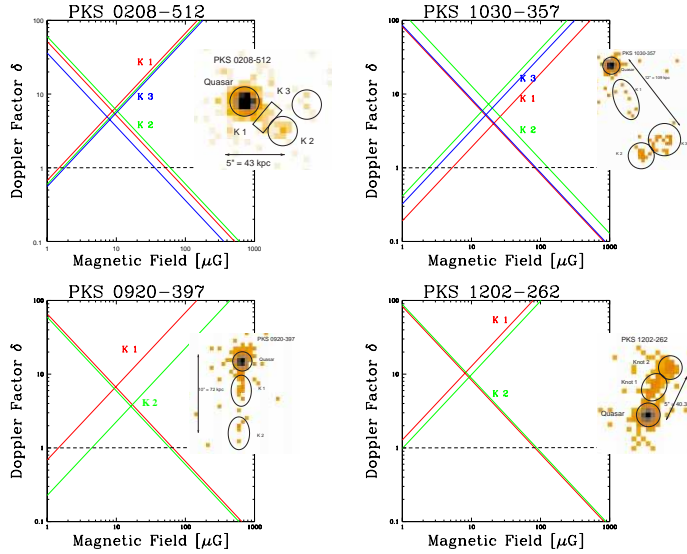


Fig. 4. *Chandra* data from four quasars with radio jets. Intersections of the lines of equipartition, $\delta \propto 1/B$, with the lines of IC/CMB production of X-rays, $\delta \propto B$, give solutions for B and δ for each region.

These four objects are shown in Figure 4. For each of the regions indicated we compare the fluxes we have measured at 8.6 GHz, and in some cases also at 4.8 GHz. For most regions our optical upper limits²⁹ prohibit extrapolating the radio flux into the X-ray region. This shows that the X-rays are not synchrotron radiation from the same population of electrons which are giving rise to the radio emission. However, the close spatial correlation of X-ray and radio emission indicates that they do arise from the same sources. This leaves inverse Compton (IC) scattering of the electrons as the most likely mechanism for X-ray emission. IC against the cosmic microwave background (CMB) is an inevitable process if the jet is in bulk

relativistic motion relative to the CMB with Lorentz factor Γ greater than a few units.^{30,31}

When we interpret all the jet regions in Figure 4 as IC/CMB emission we derive Doppler factors $\delta = (\Gamma(1 - \beta \cos \theta))^{-1}$ between 3 and 12, and equipartition magnetic fields in the jet rest frame between 5 and 25 μG . From these numbers we can calculate the kinetic flux through each element following Ref. 32, as $K = A\Gamma^2 c U$, where A is the measured cross sectional area (assuming cylindrical symmetry) and $U = U_B + U_e + U_p$ is the energy density, written as the sum of the magnetic, electron, and proton energy densities. We assume equipartition, $U_B = U_e$, and parameterize $U_p = k U_e$ and take $k=1$. We find kinetic fluxes of order 10^{46} to 10^{47} ergs s^{-1} for these jets. These numbers are comparable to or larger than the bolometric radiation from the quasar, in line with theoretical considerations showing that jets are an energetically important component of accretion processes.³³ We also see that the jets transport energy with large efficiency. The ratio of the emission radiated in the jet frame to the kinetic flux is of order 10^{-5} .

3. Conclusions

Chandra observations have discovered the evidence of large outflows of energy and material previously not seen directly. In the case of pulsar wind nebulae observations prove that jets are ejected along the spin axis, and that material is also ejected in the equatorial plane. Theoretically these would be oppositely charged plasmas.³⁴ In clusters of galaxies, the images prove a close X-ray radio connection. In quasars we have seen that the kinetic fluxes carried by jets represent very large energy contents. We might hypothesize that jets from the radio galaxies at the center of cooling flow clusters may carry similarly large energy fluxes – clearly adequate to compensate for the radiative cooling of the gas, even if we allow that the radio source only has a $\sim 10\%$ duty cycle. To actually compensate for a cooling flow probably requires a feedback mechanism involving the infalling gas and the central AGN.³⁵ Observations of the Perseus cluster of galaxies led to the suggestion that sound waves provide the mechanism for dissipation of the jet energy quasi-isotropically through the cluster.³⁶

If the X-ray emission from jets does arise from the IC/CMB, then the same objects which we have already seen would be easily detectable at any arbitrarily larger redshift at which they might occur.³⁷ This is because the emission is proportional to the energy density of the target photons, which will increase as $T^4 \propto T_0^4 (1+z)^4$, compensating exactly for the cosmological diminution of surface brightness.

This review has been based primarily on the first three years of *Chandra* operation. We are just finishing the fourth year and starting the approved fifth year program. At the *Chandra* X-ray Center we have performed a study indicating the expected lifetime of the observatory will be at least 15 years. We expect these future observations to unveil the physical processes in all astronomical systems, including the few topics included in this review, in vastly greater breadth and detail.

8 *D. A. Schwartz*

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